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# Crude Oil by Rail Accidents: Cross-industry Learning for High Hazard Sectors

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## Abstract

A sharp increase in fracking in 2008 sent crude oil production in North America soaring, leading to production quickly outgrowing existing pipeline capacity and record volumes of crude oil being hauled by rail. The high-profile crude oil train disaster at Lac-Mégantic (Canada) in 2013 was an unfortunate reminder of the dangers associated with this method of transportation and led to a permanent change in public perception alongside a re-examination of the regulatory approach. At the same time, opposition to pipeline projects such as Keystone XL meant that there remained a heavy reliance on the transportation of crude oil via rail, and there was significant resistance from rail operators towards retrofitting safety features and upgrading their rolling stock.

Six years on from the accident at Lac-Mégantic, have the right lessons been learned and applied? This paper discusses the challenges behind the transportation of crude oil by rail, identifying and examining some of the universal learning opportunities for both established and emerging high hazard sectors.

**Keywords:** learning from accidents, ALARP, high hazard, knowledge sharing

## 1. INTRODUCTION

Crude oil transportation via rail came into the public spotlight in 2013 when a freight train hauling over 70 tank cars of crude oil derailed in the Canadian town of Lac-Mégantic after an unattended brake failure resulted in the train rolling downhill from its parking spot. The significant death toll and spectacular nature of the accident (involving large fires and explosions immediately after the derailment) received widespread global media coverage. This paper discusses the challenges behind the transportation of crude oil by rail, identifying and examining some of the universal learning opportunities for both established and emerging high hazard sectors.

## 2. BACKGROUND

In the early 2000s, advancements in drilling technology combined with the use of hydraulic fracturing resulted in an increase in oil production from unconventional assets across the world, particularly in North America (Canada and the American states of Texas and North Dakota).

Oil extraction from the Bakken shale formation in North Dakota via hydraulic fracturing led to the North Dakota oil boom, resulting in record amounts of crude oil being produced. The oil underwent onward transportation to refineries and this was initially largely achieved through pipelines. However, production outstripped pipeline capacity by approximately 2010 [1], and combined with the economics of Bakken shale crude (where the high quality resulted in selling of the oil to east coast refineries for an increased profit margin) [2] resulted in an increased reliance on crude oil transportation via rail.

Whilst crude oil transportation via rail was not a new approach for the shipping of crude oil at the time, the increase over the space of less than a decade was that of almost two orders of magnitude in some cases. Association of American Railroads data [3][4] show that approximately 9,500 rail tank cars of crude oil were shipped in the USA in 2008, increasing sharply to a peak of approximately 493,000 rail tank cars in 2014. A graphical summary of this data for 2009-2018 can be seen in Figure 1 for US Class 1 railroads i.e. major railroads with annual carrier operating revenues of approximately $447 million or more [5], representing approximately 70% of the total track miles in the US [6].

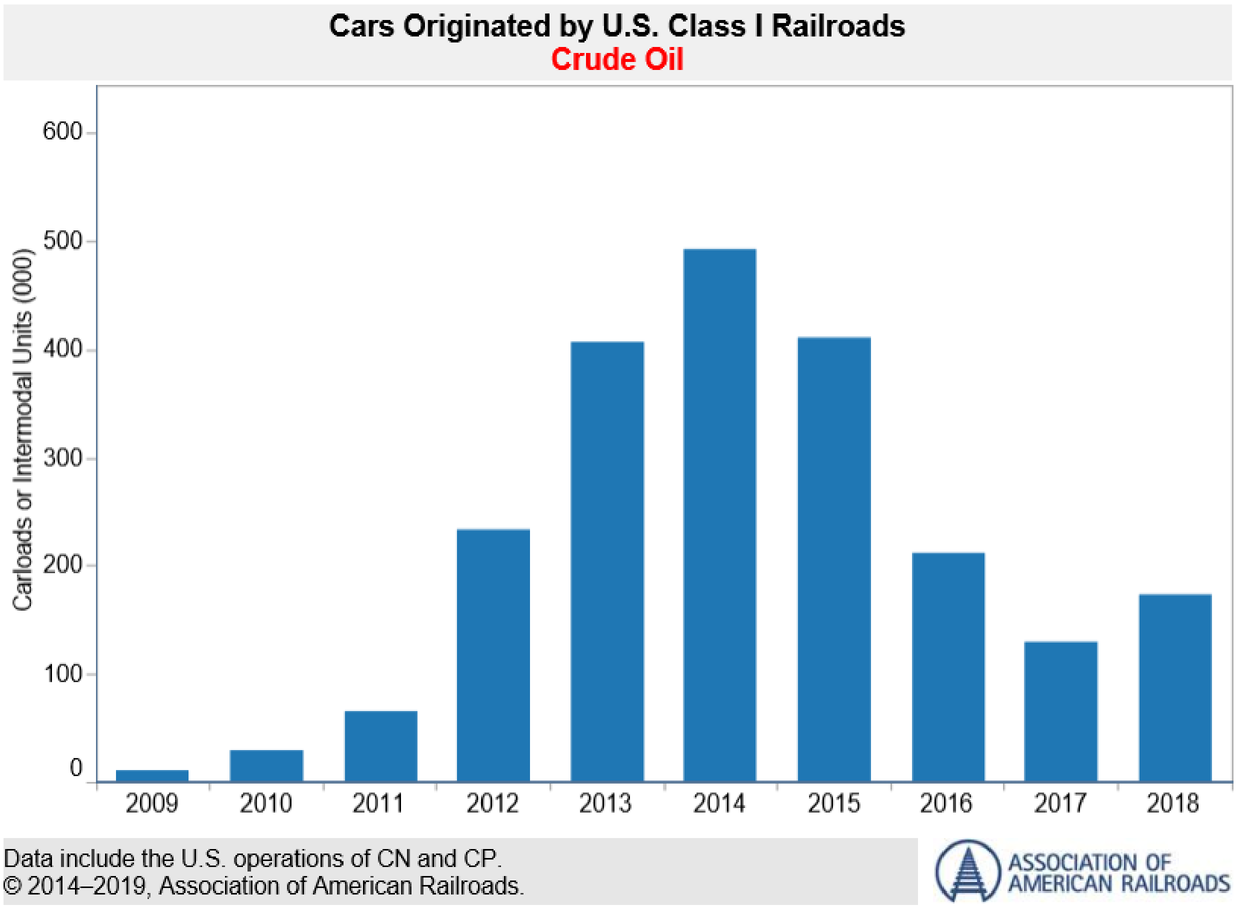


*Figure 1. Rail tank cars of crude oil hauled from US Class 1 railroads* [3]

Similar data are available for Canadian railways in a raw format from the Canada Energy Regulator [7], although the basis for the data is volume of crude oil exported from Canada via railway rather than volume of crude oil originating in Canadian Class 1 railways. Using a volume of 113,970 litres per tank car as a basis for this analysis (i.e. assuming that all tank cars are of DOT111A100W1 specification, a common rail tank car design), the available data summarised in Figure 2 shows a similar trend to the US data for years 2012 to 2016. A slight deviation between the trends in the two datasets can be seen, where the amount of crude oil transported in Canada experienced an earlier resurgence in 2017 and 2018 compared to that in the US dataset, largely related to the differential in price between West Texas Intermediate (WTI) and Western Canadian Select (WCS) crude oils, which determined the profitability of transporting WCS from Canada to the US.

Raw data are not freely available from the Association of American Railroads and as such a more direct comparison cannot be made in this paper. However, the general trends and numbers allow a useful comparison to be made regardless, demonstrating that similar sharp surges in crude oil transportation volumes were experienced in both countries in the 2010s, noting that the aim of this paper is not to investigate and explain the underlying drivers for the fluctuation of crude oil transportation via rail, other than to provide sufficient context for the reader regarding the origin of these crude oil by rail accidents.

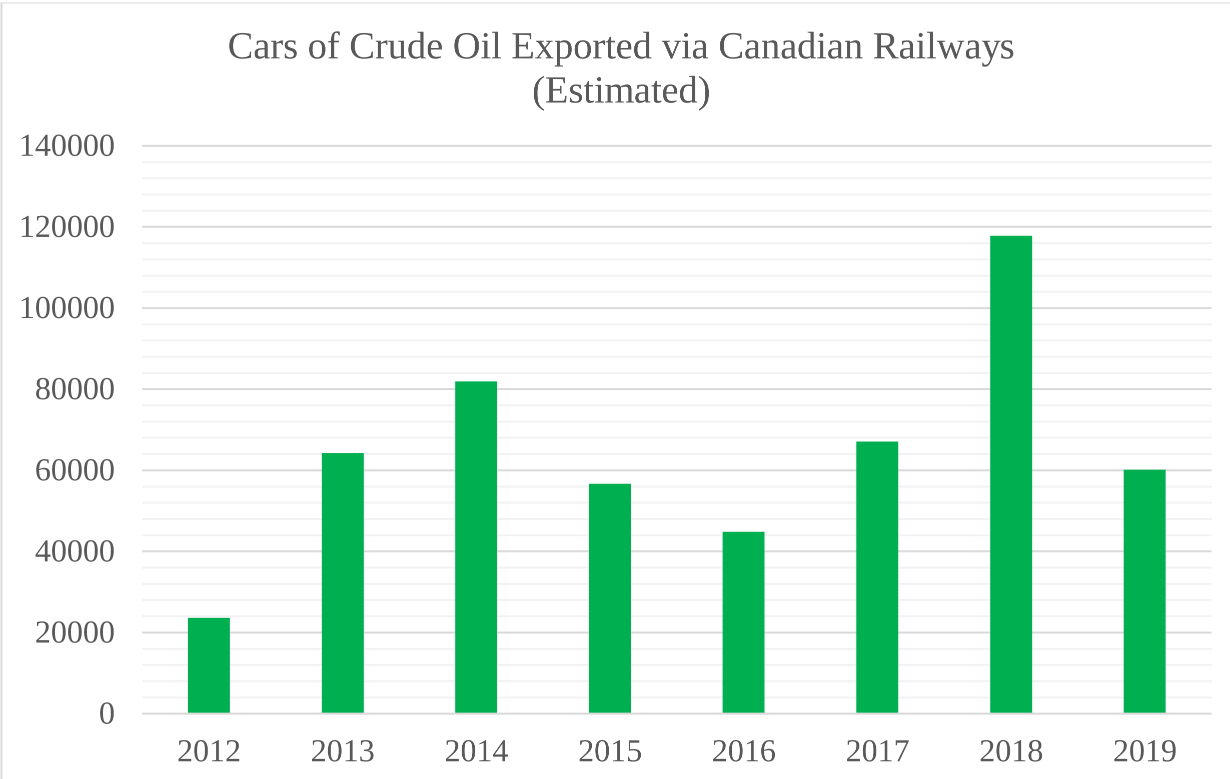


*Figure 2. Estimated rail tank cars of crude oil exported from Canada*

## 3. LAC-MÉGANTIC ACCIDENT

Montreal, Maine & Atlantic Railway freight train MMA-002 was used to transport 72 tank cars of petroleum crude oil originating from oil wells in the Bakken formation ("Bakken crude") between Farnham (Quebec, Canada) and Saint John (New Brunswick, Canada). On the 5$^{th}$ July 2013, the train stopped on a slight gradient at Nantes (Quebec, Canada) where a new crew was to continue its journey eastward in the morning after addressing some mechanical issues that were being experienced over the preceding days.

In the early hours of 6$^{th}$ of July 2013, a small locomotive fire on MMA-002 resulted in fire and rescue services attending the scene, extinguishing the fire, and securing the locomotive. Shortly thereafter, the unattended MMA-002 train began to roll down the slight gradient due to gradual brake failure, culminating in the derailment of 63 tank cars containing crude oil in the town of Lac-Mégantic some 10 kilometres downhill from the initial parking position.

The resulting fires and explosions resulted in the death of 47 people, the destruction of a large section of the downtown area (shown in Figure 3 and Figure 4), and environmental contamination of the nearby land and lake water due to the spill of crude oil.

*Figure 3. Fire following the train derailment in the city centre* [8]

*Figure 4. Lac-Mégantic town centre post-accident, showing widespread damage* [9]

## 4. REGULATORY AFTERMATH AND ACCIDENT TREND

There was widespread criticism of crude oil transportation via rail in the years following the Lac-Mégantic accident, focusing on topics such as freight train routing through heavily built-up areas, the high volatility of Bakken crude, and the low design standards for rail cars.

A common rail tank car type used in North America is the Department of Transport (DOT) Class 111 (DOT-111) model, a basic and out-dated design of which approximately 98,000 cars were still used to transport flammable liquids in 2013. Key vulnerabilities are highlighted in Figure 5:

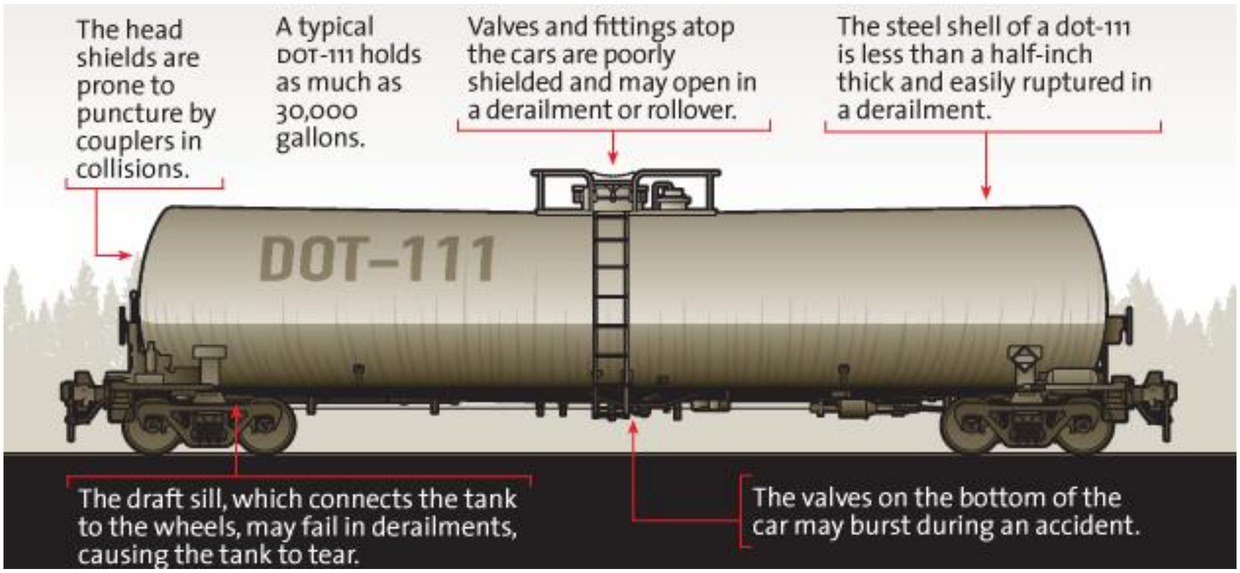


*Figure 5. DOT Class 111 rail tank car design issues.* [10]

Criticism of the DOT-111 cars was widespread even before 2013, with a US National Transportation Safety Board (NTSB) accident report on the 2009 Cherry Valley (Illinois, USA) crude oil train accident already stating that *"[…] if enhanced tank head and shell puncture-resistance systems such as head shields, tank jackets, and increased shell thicknesses had been features of the DOT-111 tank cars involved in this accident, the release of hazardous materials likely would have been significantly reduced, mitigating the severity of the accident."*[12] 'Good-faith' industry efforts towards upgrading these tank cars had already begun by 2013, with the modified DOT-111 cars (branded CPC-1232) implementing some of the upgrades recommended by the NTSB.

By December 2013, following the Lac-Mégantic accident, the NTSB's stance was that *"[…] recent railroad accidents have shown that using DOT-111 tank cars to ship flammable liquids creates an unacceptable public risk."* [13] Based on data from the Pipelines and Hazardous Materials Safety Administration (PHMSA), more crude oil had leaked from trains in 2013 than all the years since 1971 combined.

The Transportation Safety Board of Canada took a similar view, identifying a series of specific improvements for crude oil transportation via rail through their official accident report [9], formalised via five official recommendations (one of which dealt specifically with DOT-111 cars).

Retrofit and phase-out programmes were recommended by the NTSB in favour of the newer DOT-117 cars, but in some cases, this was met with significant resistance from rail operators on the basis of cost. National Steel Car (a Canadian rail car builder) confirmed that *"some of the retrofits cost more than the actual car."* [14]

A new rule created by the PHMSA in 2016 implemented the requirements of the Fixing America's Surface Transportation (FAST) Act 2015, including all major recommendations that had been advocated for by the Railway Supply Institute (RSI), an all-inclusive trade association for railway suppliers. The new PHMSA rule set deadlines for a transition from the DOT-111 to the DOT-117 standard, with an associated cost estimate of approximately 500 million USD [16]. Crude oil transportation in DOT-111 cars was to be completely stopped by 2025.

The RSI estimates that a 65% reduction in tank car fleet conditional probability of release (CPR) has taken place from 2013 to 2017 for crude oil transportation via rail as a result of a mixture of reduction in DOT-111 shipments, reduction in non-jacketed CPC-1232 shipments and an increase in jacketed CPC-1232 shipments [11]. It is anticipated that this trend in CPR will continue with the increased uptake of DOT-117 cars.

However, the momentum of gradual improvement since 2013 has been broken on a number of occasions. Most recently, braking provision requirements instituted through the FAST Act (requiring upgrading to electronically controlled pneumatic (ECP) braking from 2021 onwards) were rescinded in December 2017 on the basis of cost-benefit analysis by the PHMSA [15]. ECP braking would allow freight trains to achieve faster braking over reduced total braking distances.

Additionally, the overall improvement trend in accident rates per million miles travelled (see Figure 6) has been significantly outweighed by the concurrent sharp increase in actual distance travelled toward the end of the period analysed, which has resulted in continued accidents since 2013. Reliable data for more recent years is difficult to locate and analyse due to the widely differing bases used for data recording (i.e. the various bodies' judgement of what constitutes an accident or a spill), but it appears reasonable to extrapolate from the data in Figure 6.

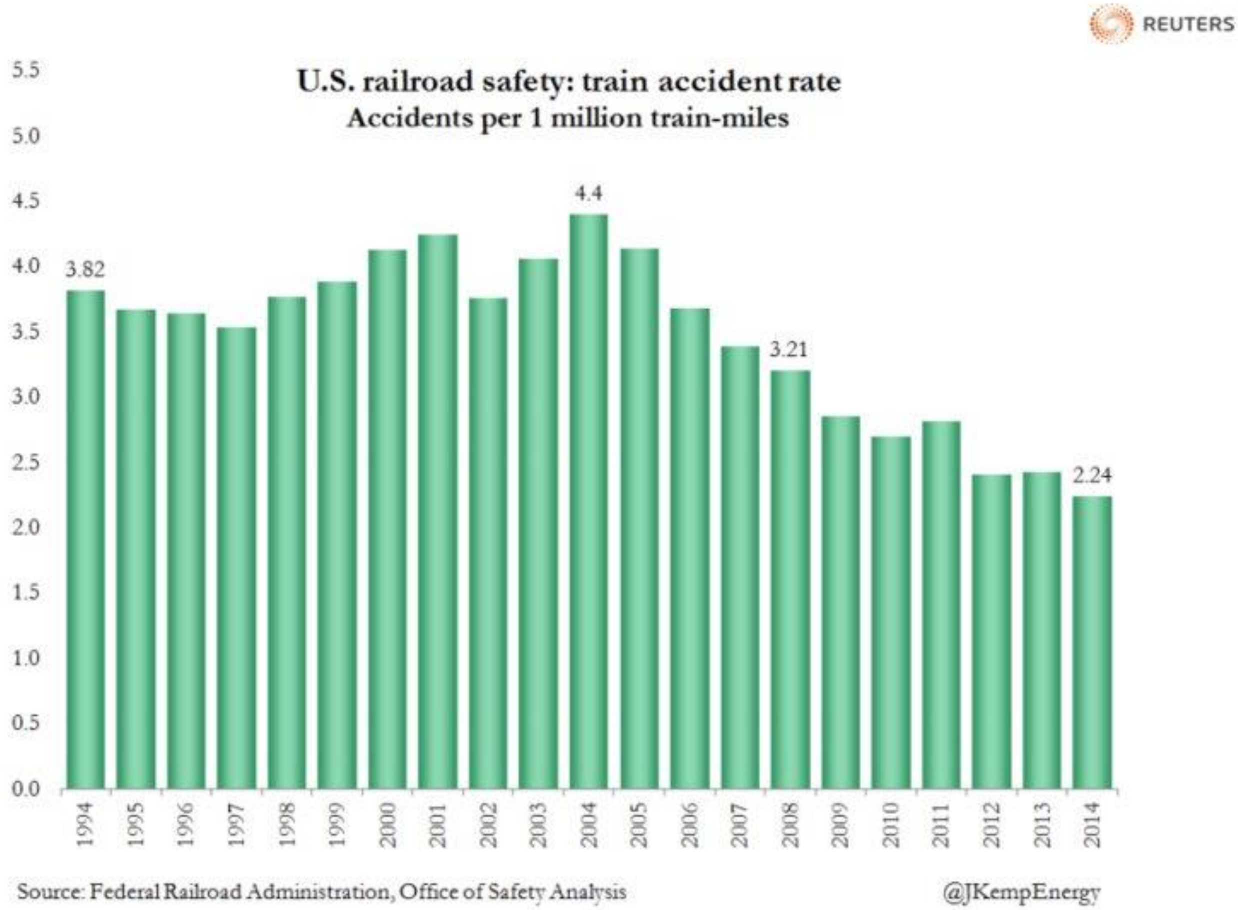


*Figure 6. Train accident rates for US railroads* [17]

An online literature review conducted for this paper has identified 21 crude oil by rail incidents and accidents in North America since the Lac-Mégantic accident in 2013, summarised in Table 1 below. Incidents and accidents were excluded where the crude oil tank cars were either empty, and where the train was predominantly carrying other cargo (with crude oil constituting a minority of the cargo). Some of the major accidents identified in Table 1 e.g. the Gogama accident in March 2015 bear a significant resemblance to Lac-Mégantic from an accident sequence perspective, and it is readily apparent that such accidents in North America are still relatively commonplace since 2013.

*Table 1. Crude oil by rail incidents and accidents, June 2013 to August 2019*

| Year | Month | Location | Explosion and/or fire? |
|---|---|---|---|
| 2013 | October | Edmonton (Alberta, Canada) | Yes |
| 2013 | November | Aliceville (Alabama, USA) | Yes |
| 2013 | December | Casselton (North Dakota, USA) | Yes |
| 2014 | January | Plaster Rock (New Brunswick, Canada) | Yes |
| 2014 | January | Philadelphia (Pennsylvania, USA) | No |
| 2014 | February | Vandergrift (Pennsylvania, USA) | No |
| 2014 | April | Lynchburg (Virginia, USA) | Yes |
| 2015 | January | South Philadelphia (Pennsylvania, USA) | No |
| 2015 | February | Timmins (Ontario, Canada) | Yes |
| 2015 | February | Mount Carbon (West Virginia, USA) | Yes |
| 2015 | March | Gogama (Ontario, Canada) | Yes |
| 2015 | March | Galena (Illinois, USA) | Yes |
| 2015 | May | Heimdal (North Dakota, USA) | Yes |
| 2015 | July | Culbertson (Montana, USA) | No |
| 2015 | November | Watertown (Wisconsin, USA) | No |
| 2015 | November | King of Prussia (Pennsylvania, USA) | No |
| 2016 | February | Pocatello (Idaho, USA) | No |
| 2016 | June | Mosier (Oregon, USA) | Yes |
| 2017 | April | Money (Mississippi, USA) | Yes |
| 2017 | June | Plainfield (Illinois, USA) | No |
| 2018 | June | Doon (Iowa, USA) | No |

Comparisons have also been made between the safety of transporting crude oil via rail versus pipeline. Analyses such as that submitted to the International Association for Energy Economics (IAEE) Energy Forum [18] have generally concluded that the conveying of crude oil via rail carries higher risk than pipelines. Some studies [19] appear to indicate that the safety aspects are approximately equal, but such conclusions should be treated with care as most such studies have been commissioned by the railway industry and thus may be demonstrating an underlying bias.

It is important to note that comparisons can be undertaken on a range of bases, with this paper focusing on preventable injuries and deaths rather than the associated (often very severe) environmental impacts of crude oil leaks.

Finally, whilst the analysis in this paper is focused on crude oil transportation specifically, there have been some major non-crude-oil chemicals trains accidents prior to 2013 bearing remarkable similarities to the Lac-Mégantic accident. The Neyshabur (Iran) train disaster in 2004 also involved a runaway train carrying flammable and explosive substances. The train rolled 20 kilometres down a hill after a parking failure (cause unknown to this day) at a railway siding at the highest point of the local area, derailing and catching fire in a city centre and finally undergoing a delayed explosion during clean-up operations. It is estimated that the TNT equivalent of the explosion was 180 tonnes [26], resulting in the death of over 300 people (largely through blast injuries up to 500 metres from the explosion centre [27]) and a blast wave that was perceptible up to 70 kilometres from the accident site [28].

## 5. SUMMARISING CAUSAL LINKS

Due to the wide range of factors contributing to the Lac-Mégantic accident, systems engineering and systems safety is judged to be the most suitable discipline approach for reviewing the accident. A range of system safety analysis and visualisation techniques can be used to visually represent the contributing factors to an accident, including techniques such as:

- Causal Analysis using System Theory (CAST) stemming from Systems Theoretic Accident Model and Process (STAMP), developed by Leveson [20];
- Functional Resonance Analysis Method (FRAM), developed by Hollnagel [21];
- Human Factors Analysis and Classification Systems (HFACS) developed by Shappell and Wiegmann [22]; and
- AcciMap, developed primarily by Rasmussen and Svedung [23][24].

The AcciMap tool is judged to be most suitable for this paper for its benefits in providing a simple, clear visual overview of the case at hand and for this paper's focus on distilling lessons from existing information, rather than aiming to uncover any new accident root causes (where more complex techniques such as CAST may be more suitable). A coarse AcciMap has therefore been constructed for this paper (see Figure 7) based on some of the contributing factors listed in the official accident investigation report [9] as well as a wider literature review on the subject.

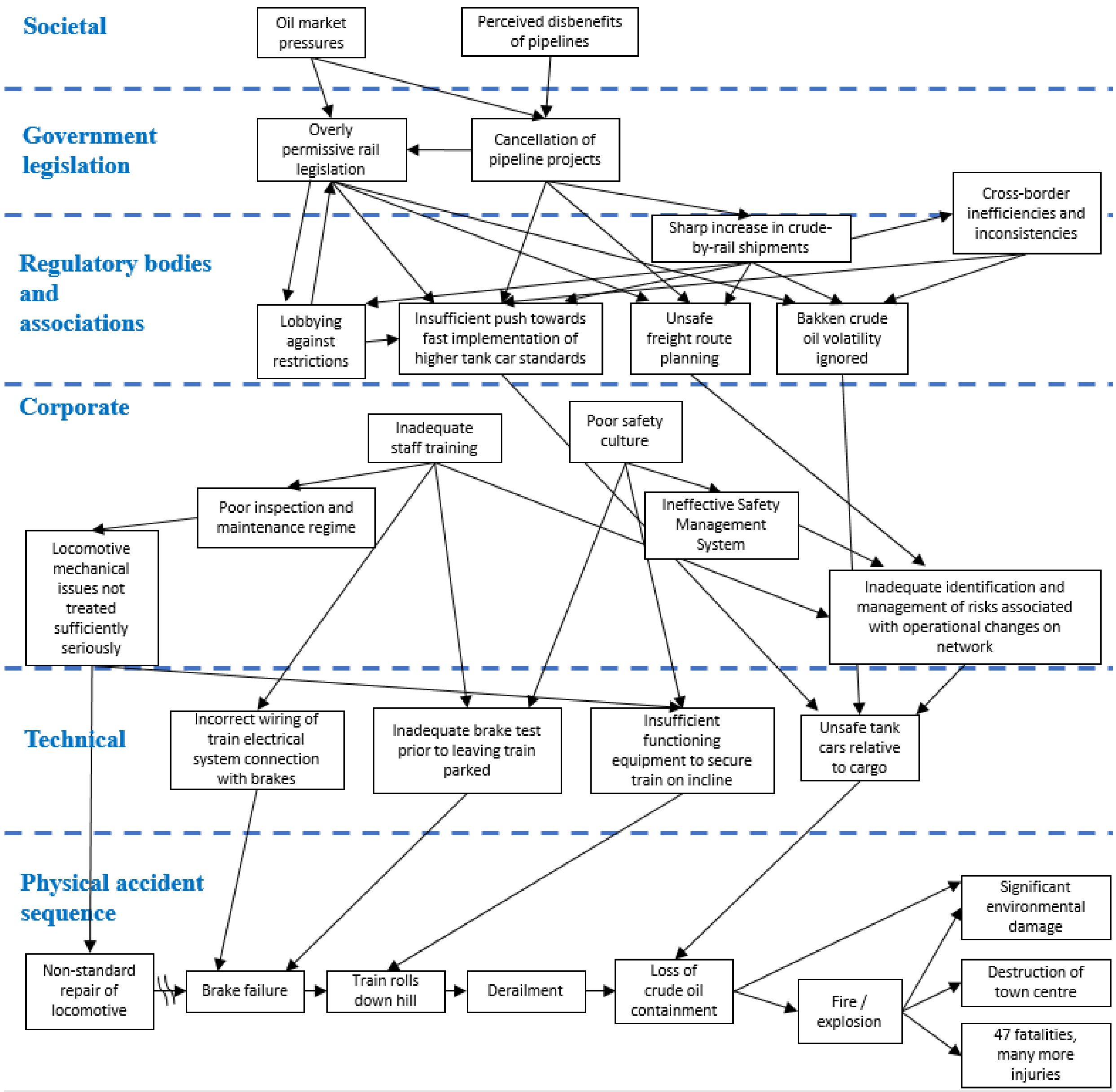


*Figure 7. Coarse AcciMap of Lac-Mégantic accident*

## 6. LEARNING OPPORTUNITIES

When investigating a major accident, there is an understandable focus on the details of the circumstances, reconstructing a detailed accident sequence such that specific causal links can be identified and rectified within the sector where the accident (and subsequent learning opportunity) occurred, and the official Lac-Mégantic accident report [9] thoroughly undertakes these tasks. However, it is important to consider whether there is commonality across many high hazard sectors in terms of both accident root causes and also high-level cross-industry lessons that can be distilled and learned.

Emerging sectors such as connected and autonomous vehicles do not traditionally fall under the ‘high hazard’ umbrella; nevertheless, new accidental and malicious risks related to e.g. use of artificial intelligence (AI) [30] may pose novel and unique low frequency, high consequence event types, whilst potentially also still showing some vulnerabilities which have parallels to older malicious attack vectors such as that used to infect Iranian nuclear centrifuges with the Stuxnet computer worm in 2010 [31]. Industry groups, researchers and intelligence organisations have become increasingly vocal regarding the security deficiencies of industrial control systems [32][33] connected to the internet with the advent of the Internet of Things, and it is important that continuous improvements are made in the interface between safety and security.

Safety professionals all have a part to play in this by actively disseminating lessons through leveraging connections with colleagues working in other sectors and lobbying their professional engineering institutions to make this an explicit aspect of engineering competencies required to achieve and maintain chartered engineer / professional engineer status. Disseminating inter-sector learning opportunities should be seen as an additional key indicator of a successful safety culture within an organisation.

Five key high-level learning opportunities are identified in this paper:

I. **Rate of change**
The rate of change of volume of crude oil transportation via rail was excessive and should have triggered a significant review of safety arrangements. Increases of over an order magnitude in any parameters within a relatively short timescale should automatically prompt review of whether a system has been correctly engineered and is being correctly managed at all levels, and whether any further changes should be made (either in parallel with the operations continuing or making the decision to halt the activity pending review) to ensure ongoing safety. Such a sudden surge in a process parameter (e.g. temperature) would not be acceptable in a process plant, and the same logic should be applied to ‘process parameters’ on a systems level in a broader sense.

II. **Characterisation of properties**
The volatility of (and therefore the degree of explosion risk posed by) Bakken crude was severely underestimated through assuming that it would be similar to more conventional types of crude oils, meaning that the safety measures in place (such as those on DOT-111 cars) were inappropriate for the hazard posed. The handling of (tangible or intangible) ‘materials’ with such significant unknown properties via processes with a different design basis should not be accepted without checks being undertaken to confirm suitability. A nuclear decommissioning plant would not feed legacy waste materials through without conducting a proper assay, and machine learning applications should be wary of the quality of learning datasets (whether of insufficient quality by chance or actively poisoned by malicious threats).

III. **Self-regulation**
Regulatory bodies being increasingly stretched thin has resulted in a general trend over the past decades toward allowing increased self-regulation across numerous sectors. The Lac-Mégantic accident and the recent Boeing 737 MAX accidents have shown that, whilst

conceptually useful, self-regulation should be used very sparingly, and only under the right conditions, taking full cognisance of the human factors limitations (such as normalisation of deviance within an organisation).

**IV. Ethical lobbying and advocacy**

The accident at Lac-Mégantic may have been avoided had a much larger network of pipelines been constructed, against public opinion (now labelling the trains in question as "bomb trains"). Studies have demonstrated that blocking of pipeline projects does not decrease crude oil production, and instead shifts the burden of transportation onto rail [34], increasing the overall risk. Public engagement and communications are now more important than ever to mitigate the hurdles posed by the general public towards sectors involving emotive subjects e.g. nuclear energy and biotechnology. This is exacerbated by the current 'post-truth' political climate worldwide. Companies and organisations across all sectors should allocate significant effort towards (ethical) lobbying and advocacy to achieve outcomes that are objectively beneficial for society.

**V. Dynamic ALARP on a holistic level**

There is a tendency in 'as low as reasonably practicable' (ALARP) demonstrations to focus on a single system being assessed, not adequately considering how system interfaces may affect the holistic risk profile. Risk reduction to an ALARP level should be demonstrated through consideration of e.g. all levels of an AcciMap diagram (especially focusing on societal, organisational and regulatory considerations) to provide evidence that residual risks have been balanced appropriately.

## 7. CONCLUSIONS

Crude oil transportation via rail over the last decade has proven problematic despite a comparatively low accident rate due to the high frequency of train derailments, very high probability of loss of containment in case of a derailment, Bakken crude oil posing a significantly higher hazard than initially anticipated, slow regulatory support and response, and

Periodic decreases in crude oil by rail accidents have largely been driven by the temporary decreases in volume transported i.e. the decreases have not been as a result of a significantly improved accident rate per unit distance travelled. Demand still significantly outstrips pipeline capacity, and thus transportation via rail is likely to remain the main mode of crude oil transportation for the foreseeable future, despite the associated risks.

It is important that, in the process of striving for improving the safety performance of this sector, wider endeavours are undertaken to apply any learnings (whether specific or high-level) to other sectors, both established and emerging.

High hazard sectors can encompass not only existing established 'traditional' sectors such as nuclear and oil & gas, but also emerging sectors and technologies such as connected & autonomous vehicles and hydrogen for domestic uses where the low frequency, high consequence type accidents can still result in significant numbers of injuries and fatalities, and where rapid development of the technologies and their implementation could lead to the repeating of past mistakes in unrelated sectors.

When looking to identify lessons, there is also a risk that overly specific lessons are identified, missing an opportunity to identify and disseminate the higher-level learning opportunities across sectors, and thus a concerted effort is needed from safety specialists across all sectors. Whilst adoption rates from lessons learned vary by several orders of magnitude across sectors, there are nevertheless significant success cases (e.g. the adoption of aviation-style checklists during surgical procedures) even in industries such as healthcare, where the adoption rate of new processes is traditionally extremely slow.

Traditional safety and risk analysis techniques are still largely relevant to the modern world, but the current fast pace of technological change can sometimes mean that there is a reduced ability to learn from past experience, and it is therefore more important than ever that all major learning opportunities are utilised to their full potential regardless of the originating sector.

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